Chapter 1

The Pleiades as a benchmark

1.1 Generalities

The ancient greeks named Pleiades to a group of stars which they believe had a common origin. These stars were the seven sisters, which, together with their parents the titan Atlas and the nymph Pleione, were put in the sky by the god Zeus.

Today we call the Pleiades cluster not just to the nine stars that made up the original Pleione family but to a much larger group, which according to Bouy et al. (2015) goes up to ~ 2100 members. This cluster is fairly close to the sun, ~ 136 pc according to Galli et al. (2017), and is also young in galactic scales, with only ~ 120 Myr (Stauffer et al. 1998). Since it is located in the solar neighbourhood it has a distinctive velocity, when compared to that of the far distant objects, of about $-16 mas/yr$ in right ascension and $20 mas/yr$ in declination. Also, it has expelled most of its cocoon gas, which gives it an almost null extinction of $A_v = 0.12$ (Guthrie 1987).

The previous properties make the pleiades the most studied cluster in the history of astronomy. In the following sections I will describe with more detail the previous properties and give others relevant for the present work.

1.2 The distance to the Pleiades

1.2.1 Measuring distances

In astronomy, measuring distances is a complicated task. Techniques vary according to the distance scale that we aim to measure. The distance ladder is constructed from smaller to larger distances. The first step in that ladder is the distance to the sun. After that, the distance to the planets and then to the stars. Since this works deal only with nearby clusters, I only explain the measuring distance to these objects.

The most direct way to measure distance to nearby stars is by means of the trigonometric parallax. This is the relative angular displacement, with respect to the far distant stars, that an object suffers in the course of a year. This relative displacement is time dependent and results from the movement of the earth (thus the observer) on its orbit around the sun. The relative displacement is maximal when measurements are taken at diametrically opposed points in the earth orbit, thus when they are separated by six months. This maximal displacement is called the parallax of the object. The distance to the object is then obtained by inverting the angular distance, measured in seconds of arc. By doing so, we obtain the distance measured in parsecs. This measurement unit gets its name from parallax-second. Thus an objects at distance one parsec from the sun shows a parallax of one arc second. The further the object is, the smaller the parallax.

As any other measurement, parallaxes had uncertainties. This uncertainties usually are a proxy for the width of the parallax distribution. Since parallaxes are related to the inverse of the distance, then the vast majority of stars had parallaxes near zero. Then, given certain precision of an instrument, and a distant object, nothing prohibits that this object may have negative measurements of its parallax. The parallax distribution is a non limited continuous distribution.

When transforming parallaxes into distances we may be tempted to take an statistics of the distribution, the mean for example, and just invert it to obtain the distance. Since this is the definition it will hold only if we have the true distance. The true distance is that in which the uncertainties are negligible. However, because measurements always have uncertainties, the inversion of the parallax will render an unbiased estimate of the true distance only for small values of the relative uncertainty (Lutz & Kelker 1973, mention that a reasonable value is below 0.15-0.20). The shape of the parallax distribution plays an important roll. If we are interested in the distance and we only have the parallax distribution, this distribution must be transformed into that of distances. However, this transformation is not a simple inversion. Several authors have proposed different approaches to the problem of distance determination using parallaxes, see for example Lutz & Kelker (1973); Bailer-Jones (2015); Astraatmadja & Bailer-Jones (2016a,b). The proper way, as Bailer-Jones (2015) points out is to infer the true distances given the observed parallaxes. For that, a prior on the distance must be established. The afore mentioned authors describe three different kinds of priors and the methodology needed to infer the true distances.

Now, I focus on the particular case of the distance to the Pleiades. The first parallax measurement of the Pleiades distance was done by van Leeuwen (1999) using the *Hipparcos* data. Later himself (van Leeuwen 2009) refined its sample and obtained a value of $120 \pm 1.9pc$. However, Gatewood et al. (2000); Soderblom et al. (2005) using also the parallaxes of smaller samples (seven and three, respectively) of stars, measured values of $130.9 \pm 7.4pc$ and $134.6 \pm 3.1pc$, respectively. Finally, Melis et al. (2014) measured $136.2 \pm 1.2pc$ using parallaxes of three stars. There is a clear controversy between *Hipparcos* data and that of the rest of the parallax measurements. This controversy will be probably solved by *Gaia*.

Until this controversy have been solved, I have decided to choose the distance found by our research group, $134.4^{2.9}_{2.8}pc$ (Galli et al. 2017). We found this distance using the kinematic parallaxes delivered by the moving cluster technique. This essentially exploits the fact that since clusters are bound, their members show a clear kinematic footprint: they seem to converge to a point in the sky (Blaauw 1964). Using this point and the velocity of the members (proper motion and radial velocities) it is possible to derive individual parallaxes.

1.3 Spatial Distribution

1.4 Velocity Distribution

1.4.1 Radial Velocity

1.5 Luminosity Distribution

1.6 Mass Distribution

1.7 The current dynamical scenario

1.8 The Pleiades DANCe DR2.

This section must contain a detailed description of the DR2 data.

Table 1.1: Pleiades DANCe DR2 properties

1.8.1 Particularities of the Pleiades DANCe DR2

As described in Section **??** the Pleiades DANCe DR2 contains astrometric (stellar positions and proper motions) and photometric ($ugrizYJHK_s$) measurements for 1,972,245 objects.

1.8.2 Selection of variables

Sarro et al. (2014) demonstrated that the most effective variables for the discrimination of members are the proper motions and the $riYJHK_s$ bands. However, they excluded the r band due to its large number of missing values in their training set. The selection of variables in this work aims at comparing its results with those found by Bouy et al. (2015) using the $\mu_\alpha, \mu_\delta, J, H, K_s, i - K_s, Y - J$ variables.

The set of variables used in this work are the stellar positions, the proper motions in right ascension and declination, μ_α, μ_δ, and the photometric colours and magnitudes, $i - K_s$,Y, J, H, K_s. However, in order to compare the results with those of Bouy et al. (2015), the analysis of the spatial distribution of the Pleiades stellar positions is done independently, in Olivares & et al. (2017b).

As described in Olivares & et al. (2017a), the photometry is modelled by parametric series of cubic spline. The parameter of this series is the colour index $i - K_s$ (in the following CI). This colour allows the most one-to-one variate-covariate relation. Figure 1.1 shows the colour-magnitude diagram (CMD) K vs $Y - J$ the second most one-to-one relation.

Figure 1.1: K vs $Y - J$ CMD for the Pleiades candidate members of Bouy et al. (2015)

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1.8.3 Data preprocessing

Since both photometry and proper motions carry crucial information for the disentanglement of the cluster population, we restrict the data set to objects with proper motions and at least two observed values in any of our four CMDs: Y, J, H, K_s vs CI. This restriction excludes 22 candidate members of Bouy et al. (2015), which have only one observed value in the photometry. Furthermore, we restrict the lower limit ($CI = 0.8$) of the colour index to the value of the brightest cluster member. We do not expect to find new bluer members in the bright part of the CMDs. We set the upper limit ($CI = 8$) of the colour index at one magnitude above the colour index of the reddest known cluster member, thus allowing for new discoveries. Due to the sensitivity limits of the DR2 survey in i and K_s bands, objects with $CI > 8$ have K_s magnitudes ≥ 16 mag. These objects are incompatible with the cluster sequence and therefore we discard them a priori as cluster members.

Our current computational constraints and the costly computations associated to our methodology (described throughout this Sect.), prevent its application to the entire data set. However, since the precision of our methodology, as that of any statistical analysis, increases with the number of independent observations, we find that a size of 10^5 source for our data is a reasonable compromise. Although a smaller data set produces faster results, it also renders a less precise model of the field (in the area around the cluster) and therefore, a more contaminated model of the cluster. For these reasons, we restrict our data set to the 10^5 objects with highest membership probabilities according to Bouy et al. (2015). Of this resulting data set, the majority (≈98%) are field objects with cluster membership probabilities around zero. Thus, the probability of leaving out a cluster member is negligible. For the remaining of the objects in the Pleiades DANCe DR2, we assign membership probabilities *a posteriori*, once the cluster model is constructed.

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